6. Enabling Technologies for Earth-Mars Communications: Part II, Power System Technologies

This chapter concludes the discussion of technical challenges and enabling technologies for realization of a high-capacity Gbps-class RF communications system at TRL 6 by the year 2020. It focuses on technologies to generate high RF transmit power and the associated prime DC power (solar cells and batteries). Thermal design and issues associated with the heat dissipation system are not included.

Both TWTA and SSPA technologies appear to be capable of supporting RF power requirements needed to close a high-rate link. However, it should be noted that TWTA-based systems capable of supporting Gbps data rates from Mars are significantly more mature than SSPA-based systems at the time of this report. Much effort has been directed at the development of high-power TWTA technology at Ka-band. Current efforts in this area are focused on moving high-power Ka-band TWTAs out of the laboratory and infusing this technology into demonstration space-flight missions and operational space- flight missions. Power combining is the current focus for laboratory development of SSPA-based devices. SSPA-based systems development is testing architectures that combine the power of dozens of discrete SSPA modules into a single amplifier. While a large number of power-combined discrete SSPA modules should be able to match the power achievable with TWTA technology, it is not clear that this approach will be able to match the overall DC-to-RF power conversion efficiency obtainable with a TWTA. However, conversion efficiency is less important for missions that employ nuclear power for propulsion. Additionally note that a power-combined architecture should provide a "graceful degradation" characteristic to SSPA-based amplifiers and mitigate concerns that may exist regarding the reliability of SSPA technology for high-power amplification at Ka-band.

Continuous technological research and improvement has occurred in the area of power subsystems. Estimates of spacecraft burden associated with the needed raw power requirements are discussed based on today's technology as well as prognostications regarding the power system technology that will be available in the 2020 timeframe. While the spacecraft burden associated with generating the necessary power for 1 Gbps system can approach 100 kg, for missions that employ nuclear power for propulsion, the needed power subsystem may be essentially "free" once the spacecraft has arrived on station.

6.1 Power Requirements

As discussed in chapter 4, the spacecraft payload power versus antenna diameter trade space is quite large with antenna diameter options spanning 6 to 25 m and RF power varying from hundreds to thousands of watts. To achieve the RF power a number of factors have to be taken into account: RF power efficiency, solar array efficiency and radiator efficiency. The technology challenge is to achieve these high RF powers at relatively low values of mass and volume. Table 6–1 provides a mass and volume summary for TWT-based power requirements in the range of hundreds of watts, with a kilowatt and beyond being achieved by power combining. Table 6–2 follows with corresponding data for SSPAs. This chapter discusses the power technologies being pursued that will lead to the results given in tables 6–1 and 6–2. It is important for the reader to note that Table 6–1 shows data for existing amplifiers that are currently at TRL 6 while table 6–2 show data for amplifiers that are at TRL 2.

TABLE 6–1.—POWER, MASS, AND VOLUME CAPABILITIES FOR TWTs

Power (watts) and device type	Eff.,%	Device		Electronic power converter (EPC)		PA mass, kg	PA mass density, kg/W	PA volume, cm^3	PA volume density, cm^3/W	Solar array mass, (assume 91 W/kg) kg	Radiator mass, (assume 67 W/kg) kg	Total mass, kg	System mass density, kg/W
		Mass, kg	Volume, cm^3	Mass, kg	Volume, cm^3								
100 (Helical Ka-band TWT)	60	2.5	3000	1.5	2250	4	.040	5250	31.5	1.8	1	6.8	.068
180 (Helical Ka-band TWT)	55	2.5	3000	1.5	2250	4	.022	5250	16	3.6	2.2	9.8	.054
250 (Helical Ka-band TWT)	50 to 55	3.0	3500	2.5	3375	5.5	.022	5250	15.1	5.0	3.1	13.6	.054
1000 (By Combining four 250 watt TWTs)	45 to 50	13	15500	10	13500	23	.023	29000	14.5	22	15	60	.060

TABLE 6–2.—POWER, MASS, AND VOLUME REQUIREMENTS FOR SSPAs

Power (watts) and device type	Eff., %	Device		Electronic Power Converter (EPC)		PA mass, kg	PA mass density, kg/W	PA volume, cm^3	PA volume density, cm^3/W	Solar array mass, (assume 91 W/kg) kg	Radiator mass, (assume 67 W/kg) kg	Total mass, kg	System mass density, kg/W
		Mass, kg	Volume, cm^3	Mass, kg	Volume, cm^3								
140	45 to 55	1.7	363	2.3	Not available	4	0.029	363.22	2.59	3.85	3.48	11.33	0.08
150	50 to 55	1.5	6144	2.5	Not available	4	0.027	6144	40.96	4.12	3.73	11.85	0.08

6.2 RF Amplifier and Power Combining

High-power amplifiers are critical transmitter components in space telecommunications systems. The two types of amplifiers most often used in space communications are TWTAs and SSPAs. TWTAs historically have been used for high-data-rate, deep space communications because of their much higher power capability, higher DC-to-RF power conversion efficiency, and greater reliability at a given power level (ref. 6–1) compared with SSPAs. Both types of amplifiers offer promising technologies for the high-capacity Mars communications channel.

The key design issues for a high-power amplifier are output power, efficiency, and mass and cooling (heat dissipation). It is complicated and difficult to compare these design parameters in detail because they involve specific design characteristics. TWTAs consist of a TWT (a microwave vacuum tube) and a high-voltage power supply, whereas SSPAs are purely semiconductor devices. As a rule of thumb, a single TWTA will produce one to two orders of magnitude more RF output power than a single SSPA. Performance improvements will continue in both technologies as new materials (e.g., high current-density vacuum cathodes and wide-bandgap semiconductors) relax previous physical limitations and sophisticated three-dimensional simulation programs encourage innovative new designs.

Both of these amplifier technologies can use some form of power-combining technology to achieve higher output power than is available from a single amplifier. As shown in table 6–3, the array feed architectures described in sections 6.2.1.2 and 6.2.2.2.2 represent important classes of power combiners. There are at times close relationships among an antenna feed system, its fine-

pointing mechanism (e.g., see sec. 5.2.2.1), and its power-combining technology. Thus, for any given mission requirement, the selection of the appropriate technology requires an integrated, detailed "strawman" antenna/power system design at a level outside the scope of this report. The sections below describe the state of the art of both families of amplifiers, along with relevant combiner technologies, and briefly discuss significant research directions. This enables one to evaluate the characteristics and fundamental limitations of amplifier technology.

6.2.1 Traveling-Wave-Tube-Amplifiers

The two key decisions in selecting a high-power amplifier are the number of active amplifier devices and the method of net output power combining. Traditional interplanetary downlinks at S-band and above (>2 GHz) use the minimum number of active devices, that is, one TWTA (not counting the normally present redundant unit) delivering from 10 to 100 W of power. Lower frequency or lower power downlinks have used solid-state amplifiers incorporating multistage binary power combining. Following considerable investment by DoD, the performance of both options has improved dramatically.

Single-stage power combining can be implemented in waveguide networks as shown in table 6–3. However, power combining can also be quasi-optical, as when multiple amplifiers independently illuminate the antenna reflector (e.g., see sec. 5.3.3). Power-combining in free space reduces resistive losses and concurrently reduces the mass and complexity of the thermal management system. The risks of RF surface breakdown and arcing are substantially reduced by over-moded and/or quasi-optical transmission. Phased-array and spatial power-combining systems present an elegant solution to the problem of single-stage power combining.

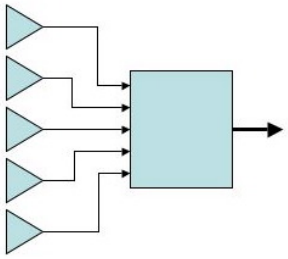
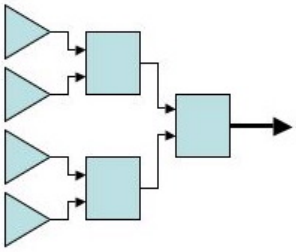
6.2.1.1 Very High Power Amplifiers

Heritage vacuum amplifiers for interplanetary space communication are helix TWTs, valued for their optimum combination of efficiency, bandwidth, and low operating voltage. For required transmitted power exceeding several hundred watts, this technology is, presently, useful only with power combining. Mars Reconnaissance Orbiter, launched in August of 2005, carries the two highest-power transmitters on any interplanetary spacecraft, a 100-W X-band TWTA and a 35-W Ka-band TWTA. In the laboratory, Ka-band technology development has resulted in a space qualified 180-W TWT (ref. 6–2). These TWTs have all incorporated helical slow-wave circuits that minimize the high voltage requirement for a given power output and maximize the instantaneous bandwidth. However, the helix circuit has the lowest thermal capacity of all the various possible slow-wave structures. The maximum feasible power from a traditional space helix Ka-band TWT is estimated to be between 300 and 500 W within the foreseeable future. Current practice in TWTAs is to use predistortion to improve linearity creating the so-called linearized TWTA (LTWTA). The predistorter (the "linearizer") is a solid-state device. However the inclusion of the linearizer only degrades the overall efficiency by about a percentage point, less for the highest power LTWTAs. LTWTAs offer the same level of linearity as do SSPAs.

Coupled-cavity TWT (CCTWT) slow-wave circuits, which are more rugged than those for helix TWTs, sacrifice bandwidth due to the fact that the additional mass tightens the boundary conditions on the electromagnetic field. The basic physics—metal accommodates heat flow but excludes RF waves—implies the well-known inverse relationship between ruggedness and bandwidth in slow-wave circuits. This relationship extends from fragile helices and their cousins (the ring-loop and ring-bar circuits) to sets of coupled resonant cavities, that is, the coupled cavity TWT.

CCTWTs have excellent efficiency and power handling ruggedness, but they operate at a higher beam voltage than a helix TWT. That they also have less bandwidth than a helix TWT, however, this is irrelevant because at Ka-band, a CCTWT still has a bandwidth greater than the full deep space allocation (31.8 to 32.3 GHz). Work at JPL (ref. 6–3) has demonstrated the feasibility of a 1-kW, Ka-band, CCTWT with 1-GHz bandwidth at a cathode voltage of 18 kV, a voltage that existing military, space-qualified, high-voltage power-supplies can reach. Higher cathode voltage could produce 2.5 kW.

TABLE 6–3.—POWER AMPLIFIER COMBINING TECHNOLOGY

	Traveling-wave-tube amplifiers	Solid-state amplifiers
Number of active devices	$1 \leq N \leq 10$	$N >> 10$
Power-combining architecture	Single stage or multistage (if required) 	Multistage binary or radial combiner 
Heritage Today (TRL 9 in interplanetary communication application)		
NEAR (LD Feb. 1996)		X-band, 5 W
Mars Global Surveyor (LD Nov. 1996)	X-band, 25 W	Ka-band, 1 W, 11% Eff.
Cassini (LD Oct. 1997)	Ka-band TWTA, 7.2 W (radio science only) X-band TWTA, 20 W S-band (radio science only) 10 W	
Deep Space 1 (LD Oct. 1998)		Ka-band, 2.2 W, 0.66 kg 14% Eff., 36 dB gain X-band, 12.5 W, 1.66 kg, 22% Eff., 38 dB gain
Stardust (LD Feb. 1999)		X-band, 15 W
Mars Reconnaissance Orbiter (LD Aug. 2005)	Ka-band TWTA, 35 W X-band TWTA, 100 W	Ka-band, 1 W, >0.6 kg 9% Eff., 15 dB gain
State of the Art Today (TRL 6 in the laboratory)		
Ka-band	180 W, 55% Eff., 50 dB gain	20 W, 8% PAE, 30 dB gain
X-band	170 W, 65% Eff., 50 dB gain	17 W net from 4 GaAs PHEMTs
Forecast State of the Art 2020 (TRL 6 in space communications demonstration)		
Ka-band	TWT: 300 to 500 W, 55% Eff. (helix TWT) TWT: 1 to 5 kW, 60% Eff., (coupled cavity TWT)	150 W, 20% PAE GaAs based 450 W, 30 to 40% PAE GaN based

Power-combined "microwave power modules" (MPMs) represent another potential approach to achieving very high RF output power. An MPM is an amplifier that attempts to minimize the mass, volume, and cost of the RF transmit chain by including in a single package the TWT, its associated high-voltage power supply (HVPS), the TWT driver amplifier (solid state), and the driver power supply. The single package allows unified cooling, RF shielding, control and protection circuits, and mechanical support. The MPM partitions the total gain between the vacuum amplifier and the solid-state preamplifier/power amplifier in an optimum fashion, allowing the TWT to be a miniaturized device that is significantly shorter than a standard TWT, with proportional savings in mass and volume. Since its first demonstration in 1993, the MPM has found application in military airborne systems, but to date has not been used in space. A space MPM, as opposed to a straight SSPA, may have potential for a power-combined architecture.

In the long term, vacuum amplifiers with multiple electron beams may provide 10 kW or more from a single compact device (e.g., multibeam klystron), although this work is presently at a very low TRL. For the foreseeable future transmitted power above a few kilowatts will require power combining.

High-power TWTs generate waste heat equal to about one-half of input DC power. Most of the heat appears at one end, in the collector. Thermal management approaches for TWTs can be simple or complex depending on how far the heat must flow from the TWT to a radiator. Some common heat dissipation mechanisms are the following:

- The TWT may be purely conduction cooled to its mounting platform, with the platform cooled by radiation or conduction. This is the usual method.
- Heat pipes are typically used for transferring TWTA waste heat to the spacecraft radiator(s).
- The primary radiator may be a set of fins directly attached to the TWT collector. This is elegant but requires mounting the radiating TWT fins on the outside of the spacecraft, and limits the layout flexibility of the RF transmitter chain. Some waste heat is still generated in the TWT circuit and must be conducted to the TWT mounting platform. This platform, in turn, must be cooled.

The extended interaction klystron (EIK) is also of interest for high-power amplification if one can accept the bandwidth compromise. Existing designs for EIKs have the potential for high duty cycle operations that provide 3 kW of power in a single device, thereby reducing system complexity and mass over a power-combined TWT system. The strength of an EIK is that it can produce a given output power at a lower cathode voltage compared to a coupled cavity TWT. But the coupled cavity TWT is an intrinsically broader bandwidth device. The higher cathode voltage of the TWT makes the beam more collectable at any given output power, and therefore, the TWT can offer a higher overall efficiency, similar to a TWT when a multistage depressed collector is used. It is estimated that an EIK could support ~1.5 percent bandwidth at 50 percent efficiency. Thus, with technical advances, bandwidth may be adequate at Ka-band, assuming operation is limited to a single band. Increased phase distortion (over TWT) could limit the types of modulation to lower order.

The above discussion assumes the current practice, which views active cooling systems on spacecraft as unacceptable. Current commercial geosynchronous satellites use passive heat pipes for payloads that now approach 15 kW of total prime power. As RF power requirements increase, overall power-added-efficiency reaches a limiting value, and active cooling systems will have to be considered.

6.2.1.2 Power-Combining Techniques

As discussed in the preceding section, power amplifiers can be designed either as a single high-power device or by combining a set of comparatively lower power amplifiers. The choice between these architectures will depend upon the required output power, requirements for fine-beam pointing, and packaging constraints. This section discusses significant issues in implementation of TWTA power combiners.

6.2.1.2.1 Waveguide Power Combining.—Five power-combining approaches for achieving 1 kW over the DSN frequency band were recently considered for various NASA research projects:

1. Binary magic-T hybrid junction
2. Magic-T hybrid coupler (N > 2)
3. Radial waveguide structures
4. Spatial power combining
5. Array feeds, including feed horn arrays and phased arrays

Of these, only spatial power combining and array feeds hold promise of reliability in 10-kW systems, as justified in the following text.

Research on a two-way combiner based on the waveguide magic-T hybrid junction was proposed and conducted at NASA. The test circuit shown in figure 6–1 represents the general configuration of a two-way combiner. The magic-T and port configuration are shown in figure 6–2, and the variations in sum and difference port output powers with change in phase are shown in figure 6–3. This was the first successful demonstration of high-efficiency, high-power combining at Ka-band and was done initially with two 110 to 115 W ACTS TWTAs (29.1 to 29.6 GHz) (ref. 6–4), and then with two 32-GHz 100-W TWTs (Model no. 999H) (ref. 6–5). The power combiner testbed for the two 32-GHz TWTs is shown in figure 6–4. Typical combining efficiencies of 90 percent or better were achieved. Higher efficiency may be possible if an optimized, custom design is used in place of the commercial parts used here.

A parallel effort consisting of the computer modeling of the magic-T and alternative hybrid junction configurations was performed using CST Microwave Studio to investigate improvements in efficiency and power handling capability (ref. 6–6). The results show that the magic-T and “folded E-plane” junctions can be designed for low loss (<0.1 dB and >95 percent efficiency) and high power (kilowatts). The combiner circuit was modified to compensate for the very different rates of change of phase with frequency of the two TWTs and the corresponding RF input circuits in order to maintain phase balance at the input ports of the magic-T. One important result is that the useful bandwidth of the magic-T was extended to that of the TWTs over a demonstrated bandwidth up to 3 GHz. The efficiency over a 1-GHz frequency band, shown in figure 6–4, was around 90 percent, which is good for the fully optimized test circuit.

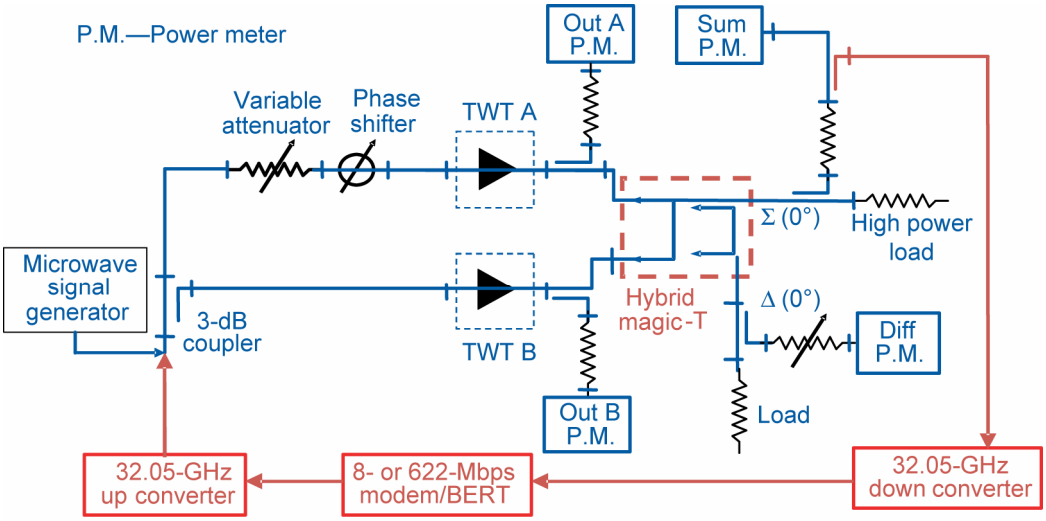


Figure 6–1.—Two-way waveguide combiner test circuit.

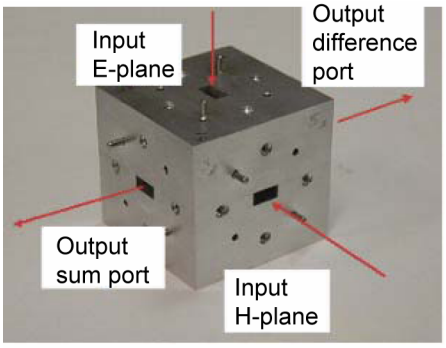


Figure 6–2.—Four-port magic-T junction.

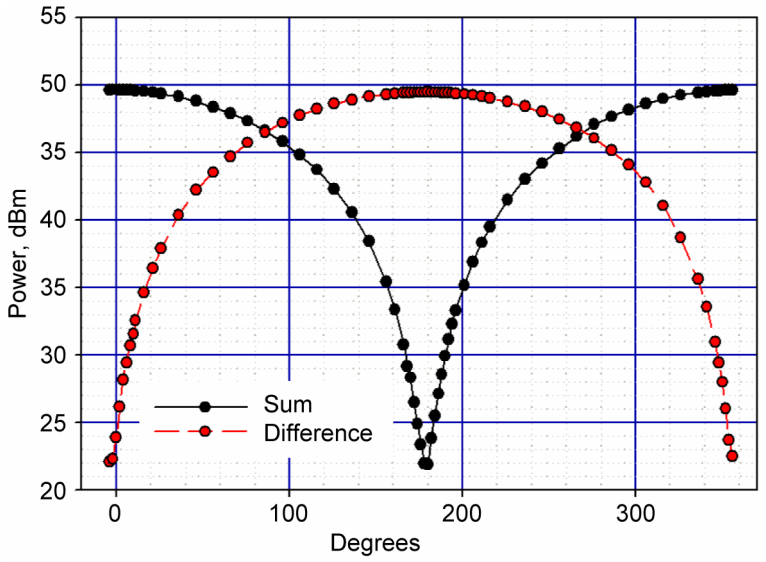


Figure 6–3.—Magic-T sum and difference output power variations with change in phase.

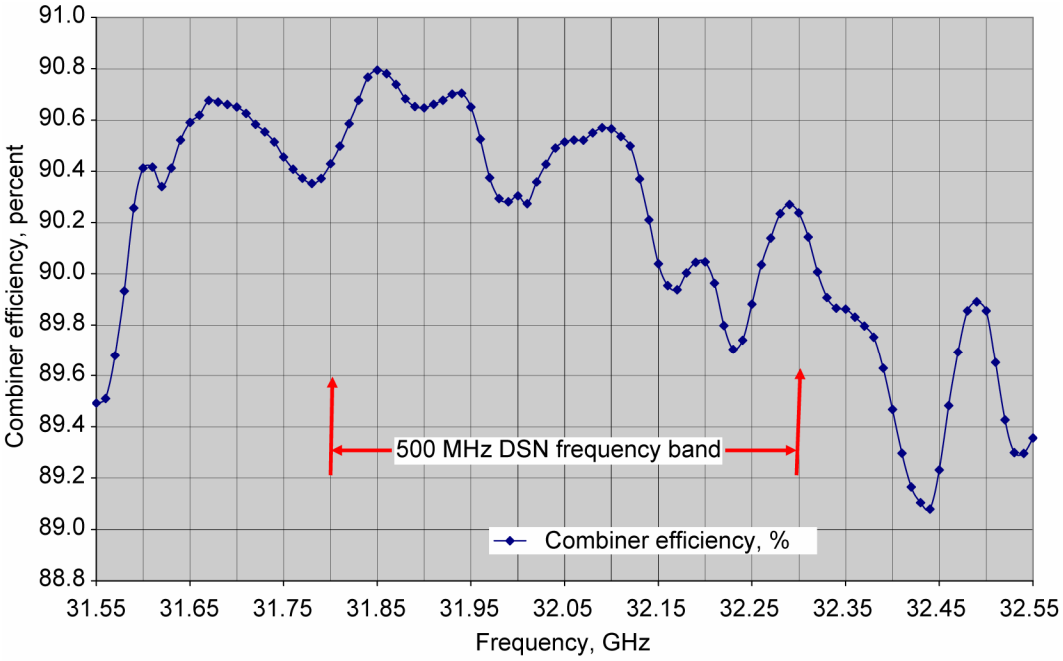


Figure 6–4.—Combiner efficiency over 1-GHz frequency band.

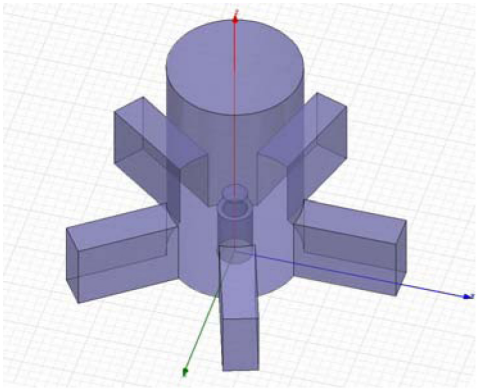


Figure 6–5.—Five-way radial combiner design (courtesy of Raul Perez, Jet Propulsion Laboratory).

A more significant result was the successful demonstration at a carrier frequency of 32.05 GHz of a high data rate of 622 Mbps (QPSK) with a low BER (2.4×10^{-8}). Error-free data transmission at 8 Mbps (BPSK and QPSK) was also successfully demonstrated. Because of the narrow signal bandwidth, successful transmission was not dependent on correction of the phase imbalance. This is consistent with the fact that the combining efficiency of the magic-T is relatively insensitive to phase differences of a few degrees at the input ports.

L–3 Electron Technologies, Inc. (formerly Boeing) investigated magic-T/hybrid couplers for the combination of four through eight TWTs and also did a comparison between the magic-T and the JPL five-way radial combiner design (shown in fig. 6–5). The recommendation of the study, based on consideration of cost, complexity, and risk, was the use of either four-way or eight-way magic-T technology to generate 1 kW. For eight or fewer TWTs, the magic-T alone or magic-T/hybrid combination was preferred to radial combining.

An assessment of the capability to produce up to 10 kW at 37 GHz, including required technology development, was performed at JPL. A block diagram of a four-way power combiner based on the use of four active CCTWTs and one cold spare is shown in figure 6–6. The four-way power combiner configuration shown in the figure is basically the same needed for 32 GHz and also for a 1-kW power combiner using helix TWTs.

6.2.1.2.2 Thermal Limitations on Waveguide Networks.—Above 1 kW, any Ka-band waveguide network must be kept short and simple: short, because at 1-kW CW (continuous wave) even small resistive losses will require either radiative, or worse, active cooling; simple, because power combiners, switches, and other waveguide components will be extremely difficult to cool, protect from arcing, and keep free of multipactor effects under all conditions. Indeed, the antenna geometry may be limited by the need to place the feed horn(s) adjacent to the high-power amplifier(s). For any downlink transmitter above 1 kW, or even above a few hundred watts, reliability concerns dictate keeping all spacecraft structures far from regions of high RF power density. This caution includes waveguide components, which are no more immune than any other surface to overheating, arcing, or multipactor phenomena.

Figure 6–7 quantifies the thermal limitations of high-power Ka-band waveguide without the benefit of radiative or other cooling. On the vertical axis is the CW power flow in the waveguide; on the horizontal axis, the length of waveguide that is 200 °C hotter in the center than at the (heat sunk) ends. The red lines are for standard WR–28 waveguide, 0.28 × 0.14 in. Green lines correspond to a proprietary low-loss waveguide, 0.4 × 0.7 in., produced for satellite communications applications by Antennas for Communications, Ocala, FL. Note that figure 6–7

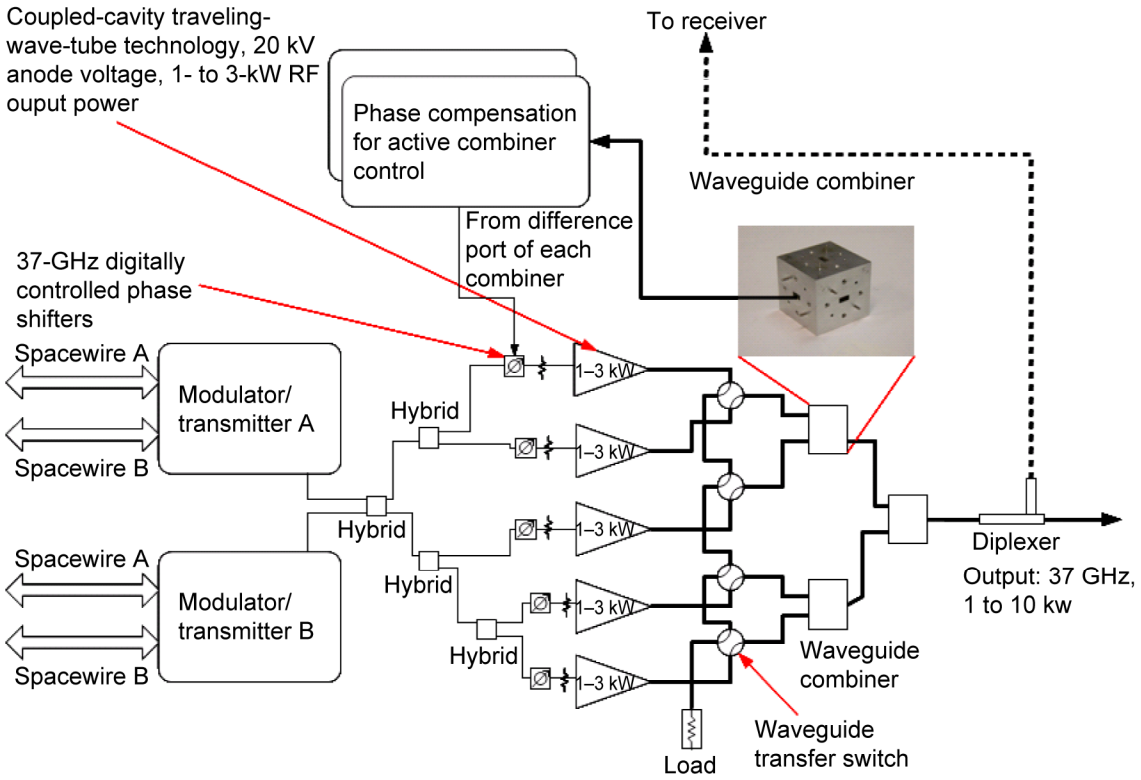


Figure 6–6.—Block diagram of four-way waveguide combiner (four active TWTAs with one cold spare): shown here for 37 GHz, but also applicable to 32 GHz (courtesy of Raul Perez, Jet Propulsion Laboratory).

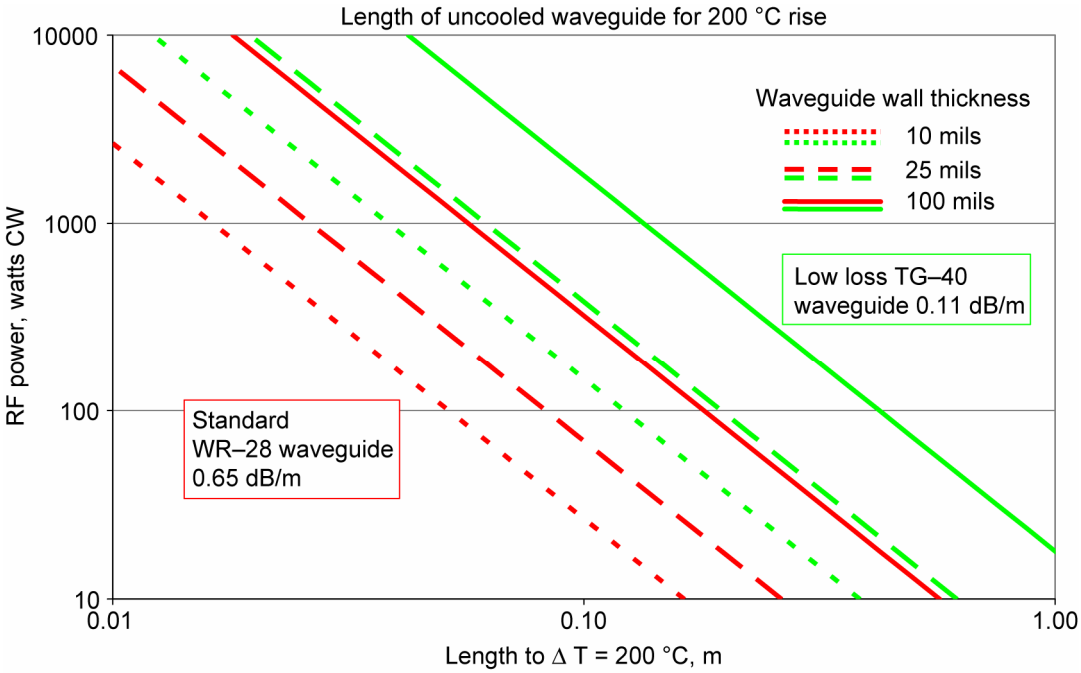


Figure 6–7.—Thermal limitations of high-power Ka-band waveguide (without radiative cooling).

addresses thermal limitations only—the highest power levels illustrated are unrealistic due to RF breakdown.

Both waveguide models are evaluated for three different wall thicknesses: the 10- and 25-mil grades of commercial WR–28, and a highly conductive 100-mil wall. The maximum-free, uncooled length is calculated assuming that both ends are cooled and that the maximum tolerable temperature differential between the heat sinks and the middle of the uncooled waveguide run is 200 °C. Single-mode, thin-walled WR–28 appears to be useless because 10 W of RF will overheat a 20 cm length of uncooled waveguide. If the RF power is a kilowatt, then even the best-performing 100-mil wall, low-loss waveguide is inadequate for uncooled runs of 20 cm. Obviously, thermal issues are significantly reduced by placing the high-power amplifiers directly adjacent to the antenna feeds; this holds true for both vacuum and solid-state amplifiers.

Colocation of the power amplifier with the antenna presents the opportunity to develop systems that employ spatial power combining, thereby eliminating losses associated with power divider networks (see sec. 5.3.3.1).

6.2.1.2.3 Power-Combining Summary.—Different approaches and options are suggested depending on power level required with respect to vacuum amplifier and power combiner technologies.

At or below the 1-kW level, single TWT solutions may be feasible. Depending on the nature and details of the mission, power-combined TWT solutions may be posited as the working approach with magic-T or other combiner architectures.

At the kilowatt level, successful demonstration of high efficiency, high-power combining—with potentially large bandwidth and high-data-rate transmission (622 Mbps), along with power-combining studies—indicates power combining using the magic-T as the most promising approach to meeting a 1 Gbps, 1 kW requirement. Performance may be extended, possibly up to 10 kW, depending on the availability of TWTs and power supplies with sufficient power and

adequate waveguide combiner power handling capability. In the long term (2020), more exotic vacuum amplifiers, for example, multibeam klystrons may also provide up to 10 kW from a single compact device, but bandwidth may be a limitation that has not yet been addressed.

At power levels beyond 10-kW quasi-optical architectures would limit the peak field stresses to manageable levels.

6.2.2 Solid-State Power Amplifier (SSPA)

6.2.2.1 SSPA Alternative

As shown in table 6–3, an SSPA has been shown, in the laboratory (TRL 6) to generate tens of watts at Ka-band utilizing a multistage combiner of $N > 10$ devices. It is predicted that this technology will be capable of achieving up to 450 W in a space demonstration (TRL 6) by 2020.

6.2.2.1.1 Overview.—SSPA is a newer class of power amplifier technology that has recently reached a level of maturity and is becoming available for space-based telecommunication applications. In many cases, particularly at lower frequencies, SSPAs are the preferred option, depending on the system tradeoffs. SSPAs are envisioned for use for applications where moderate power is required and efficiency is not the limiting factor. Most implementations follow the classical single "brick" form factor SSPA with multiple gain stages within the brick, usually in conventional binary power-combining schemes. For higher power applications at higher frequencies, such as Ka-band, novel methods of power combining and higher efficiency devices are required to reduce power consumption and dissipation, which impact system efficiency.

This section will briefly describe emerging technologies in SSPA and combining architectures, and how they can be exploited in transmit arrays. First, we describe the role that solid-state amplifiers can play in addressing telecom needs for NASA applications then we discuss the importance of new semiconductor technologies and power combiners that have been developed. The use of power combining allows solid-state technology to reach TWTA power levels, at Ka-band.

6.2.2.1.2 System Considerations in Selection of Solid-State Devices at Ka-Band.—There are several characteristics of SSPAs that are key to selection of this technology. These include issues such as reliability, efficiency, linearity, drive voltage, etc. Due to the pivotal nature of the communications system onboard spacecraft, the reliability of the final power amplifier is of paramount importance.

The factors that influence reliability for an SSPA are quite different than for a TWTA. While vacuum tube amplifiers can also be employed in a distributed amplifier architecture, solid-state amplifiers are typically smaller devices than TWTAs and are thusly are more suited to use in electronically scanned phased-array antennas or other systems where a multitude of separate amplifiers are desired. An architecture that relies upon combining power from a large number of relatively low power amplifiers can enhance overall system reliability through the statistical concept known as graceful degradation. The low-power solid-state elements also have potential to improve reliability because they employ supply voltages that are 100 to 1000 times smaller than those used by vacuum tube electronics. The extremely high voltages required for vacuum tube electronics limits the overall reliability of the amplifier and introduce additional failure mechanisms such as corona. Nevertheless, at present, the overwhelming majority of amplifiers used in space are TWTAs and these devices have proven to be highly reliable. In contrast, only limited data to date has been amassed on SSPAs. While SSPA reliability is improving, to date it is not yet commensurate with a TWTA.

While the operating efficiency of solid-state technology is much less than that associated with vacuum tube electronics, steady improvement in device efficiency has occurred in the laboratory. Other considerations include the fact that the bandwidth of solid-state devices is large, and linearity over this bandwidth is amenable to modern, bandwidth-efficient modulation and coding schemes that achieve high bits/Hz usage of allocated bandwidth. There are tradeoffs, however, and the solid-state designer must properly deal with issues such as isolation, dc bus control, increased power dissipation, etc., that may not be encountered when generating equivalent power from a single TWT. Recent advances at NASA, industry, and academia suggest that higher power levels for solid-state amplifiers at Ka-band are becoming feasible, and near-term demonstration power levels of greater than 40 W are planned at NASA.

6.2.2.1.3 Solid-State Arrays and Implication on Pointing/Antennas.—At Ka-band, and especially for deep space missions, the "pointing problem" is a recognized effect related to the size of the antenna aperture. The antenna is often designed to be large for total EIRP, causing the associated beamwidth to be sufficiently small that accurate pointing of the antenna requires a fine-beam-pointing system, as previously discussed in section 5.1.4.

Phased arrays are suitable for resolving this issue by electronically changing the angle of radiation; this beam steering may be implemented in a number of ways. Arrays can range from full-scan, nonmechanical implementations to partially articulating subpanels or secondary panels that change the focus on a larger nonmoving antenna. Solid-state distributed amplifier approaches lend themselves to all these applications. Recently there has been renewed interest in approaches to solving the fine-pointing problem with arrays, as conceptually illustrated in figure 6–8, where a transmit/receive system with monopulse capability combines solid-state power generation and pointing functions. It illustrates how the use of a phased array for the transmission can replace the need for an adjustable mirror. In the case of the TWTA, the moveable (fine-adjust) mirror is required. For a solid-state phased array, the moveable mirror is eliminated and replaced by scanning of the array. The electronic alternative to the moveable mirror is its replacement with a reflectarray to affect pointing. The solid-state configuration makes distributed amplifiers an attractive alternative to TWTAs for pointing applications.

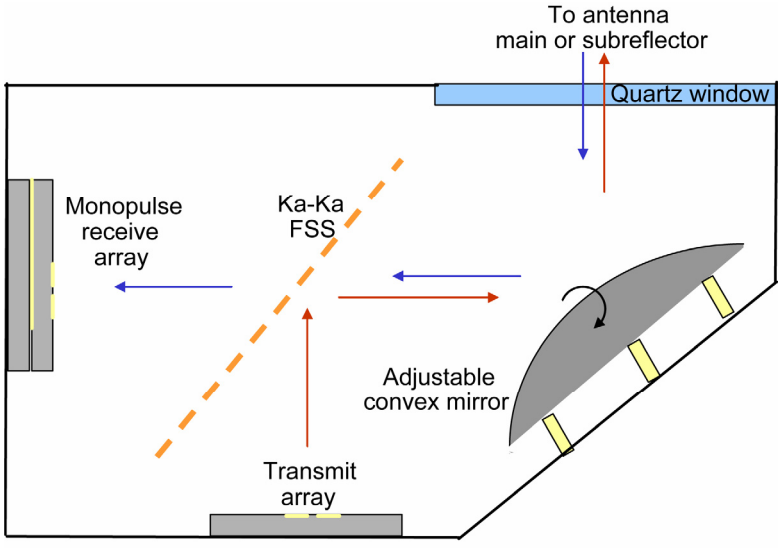


Figure 6–8.—Conceptual phased-array fine-beam-pointing system.

6.2.2.2 Emerging Technologies in Solid-State Power

6.2.2.2.1 Emerging Technologies in SSPAs.—SSPA development has recently focused on advanced semiconductor technologies for improved performance, reliability, and robustness. Wide-bandgap semiconductors such as gallium nitride (GaN), silicon carbide (SiC), and other III-V based devices have assumed a larger role due to their inherent advantages over traditional silicon-based devices and gallium arsenide (GaAs). Currently, much effort is being expended by the (DoD), the Missile Defense Agency (MDA), and the Defense Advanced Research Projects Agency (DARPA) under its Wide-Bandgap Semiconductor Initiative, to further develop these promising SSPA technologies. The commercial sector is participating and investing in the development of these technologies as well as for the cellular and base station markets.

Wide-bandgap semiconductors exhibit properties that make them potentially superior in most areas to current GaAs and LDMOS (Lateral Diffused Metal-Oxide-Semiconductor) high-power amplifiers at millimeter-wave frequencies. A contributing factor is their inherent ruggedness, that is, high operating voltage, large bandwidth, high radiation tolerance, and high power density. This technology may reach commercial insertion within 5 years.

In the Ka-band regime, GaN offers significant performance improvements over GaAs as an RF power device technology. With GaN Ka-band devices in the 1 to 3 W level, MMICs at 5 to 10 W, and demonstrated efficiencies ranging from the upper 30 percent to over 50 percent, GaN amplifiers promise to become attractive in increasing numbers of applications. Some key performance metrics are listed below (ref. 6–7).

- GaN device-level power densities exceeding 10 W/mm at 10 GHz have been demonstrated, whereas GaAs power density is limited to approximately 1.5 W/mm at 10 GHz. Power densities of at least 5 to 10 W/mm are being reported at Ka-band.
- GaN devices should be able to operate at extremely high temperatures (>250 °C). GaAs devices have an effective limit of approximately 150 °C.
- GaN devices have higher RF output impedance, implying greater power-bandwidth products, and consequently possessing bandwidth inherently wider than that of GaAs-based amplifiers.
- GaN devices have 2.5 times the bandgap energy and 3 times higher electron saturation velocity than GaAs. This can permit GaN devices to sustain two orders of magnitude higher voltage levels than GaAs (i.e., from under less than 1 V to almost 100 V). This higher operating voltage allows for more efficient power distribution.

6.2.2.2.2 Power Combiners.—Low loss power combiners producing up to 10× improvements in insertion loss across 10 to 15 percent bandwidths at Ka-band have been demonstrated (ref. 6–8). These recent technology developments can be tailored to specific mission telecom objectives for systems using solid-state devices: specifically, instruments, phased arrays, formation flying, and applications requiring scalable, low-cost Ka-band power. Depending on required bandwidths, efficiency can be optimized. A key element to consider for ultra-low-loss combining is moving the RF from a substrate-based transmission line topology (RF microstrip or coplanar waveguide) to waveguide to eliminate on-chip combining losses. Classical binary combiners such as the Wilkinson type, though well understood and effective in many applications, will not provide the needed system efficiency to allow solid-state systems to scale to TWTA power levels (120 to 150 W) at Ka-band. Novel power-combining schemes are being

developed to yield SSPAs with 40 percent efficiency (ref. 6–9) at these power levels. These approaches demonstrate the low-loss combining and phase stability required to provide alternatives to TWTA-based systems at Ka-band.

The graphic in figure 6–9 depicts combiner efficiency at Ka-band based on the classical binary combining approach, which has impeded the development of SSPAs at Ka-band. Since this combiner exhibits combining efficiency of 0.4 dB of loss per stage, the combining efficiency decreases as the number of amplifiers stages increases. Eliminating or substantially decreasing this output combining loss for large '*N*' combining, where *N* represents the number of devices combined, has led to several technology developments. To achieve reaching the requisite combining efficiencies, high-efficiency combiners at the device and MMIC level are required. The overall reliability of a power-combined system has not yet been evaluated. Such an analysis needs to take into consideration all possible modes of failure and not be restricted to simple models of "single amplifier failure" only.

Proof-of-concept combiners based on waveguide radial and waveguide binary combiners have been shown to exhibit the characteristics desirable for high-power Ka-band operation (ref. 6–8) (see fig. 6–9). That is, hardware demonstrations have shown that the output loss of a Ka-band combiner can be reduced to less than the 1 to 1.5 dB required to achieve an SSPA efficiency of 40 percent with GaN MMICs (see fig. 6–10).

As an example, using a septum combiner, a 120-W-class Ka-band amplifier with 40 percent power added efficiency (PAE) is feasible using waveguide binary combining (ref. 6–9). Additional work is being pursued to expand the combining of multiple 120-W-class amplifiers into a 1-kW-class solid-state transmitter for terrestrial applications. The approaches for kW-level power are the same as power combining of TWTAs as discussed in section 6.2.1.2.1. In the example shown below a COTS product is compared to a recently developed Ka-band septum combiner (ref. 6–11) that is suitable for binary waveguide combining. Figure 6–11 shows the benefits of the septum combiner in enabling the combination of a higher number of MMIC amplifiers to reach TWTA-like power levels.

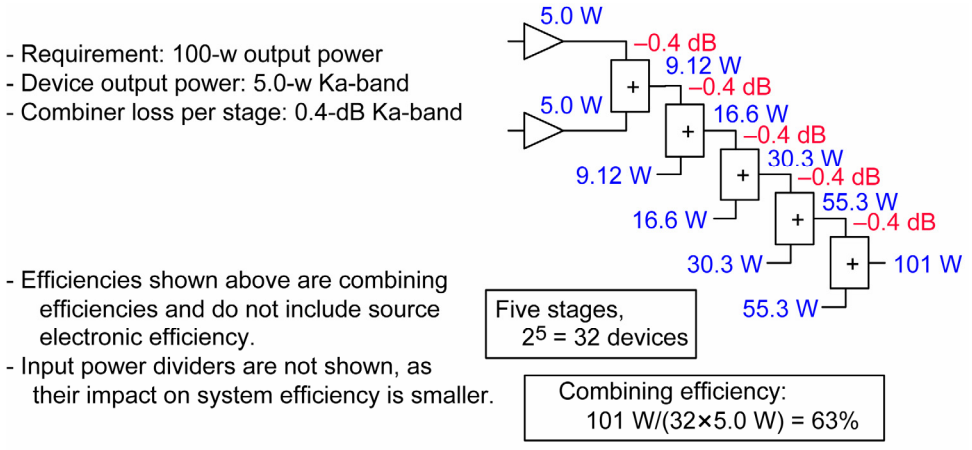

- Requirement: 100-w output power
- Device output power: 5.0-w Ka-band
- Combiner loss per stage: 0.4-dB Ka-band
5.0 W
–0.4 dB
9.12 W
5.0 W
–0.4 dB
16.6 W
–0.4 dB
30.3 W
9.12 W
–0.4 dB
55.3 W
16.6 W
–0.4 dB
30.3 W
101 W
55.3 W
- Efficiencies shown above are combining efficiencies and do not include source electronic efficiency.
- Input power dividers are not shown, as their impact on system efficiency is smaller.
Five stages, 2^5 = 32 devices
Combining efficiency: 101 W/(32×5.0 W) = 63%

Figure 6–9.—Classical Ka-band power combiner efficiency.

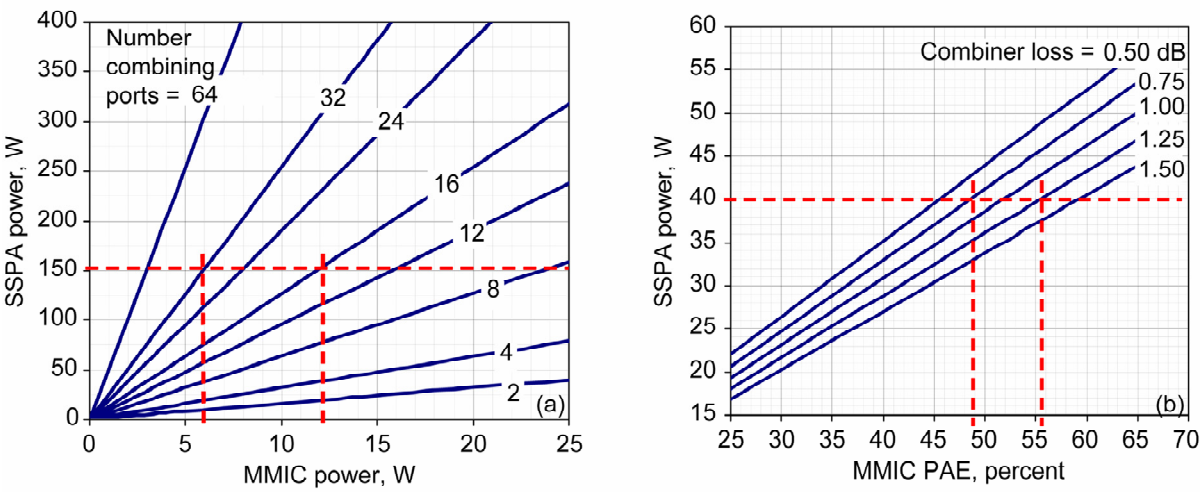


Figure 6–10.—SSPA power and efficiency are related to the power and efficiency of the combined MMICs and the combiner loss: SSPA versus MMIC (ref. 6–7). (a) SSPA power versus MMIC power assuming combiner loss = 1 dB. (b) SSPA power versus MMIC power assuming MMIC gain = 10 dB.

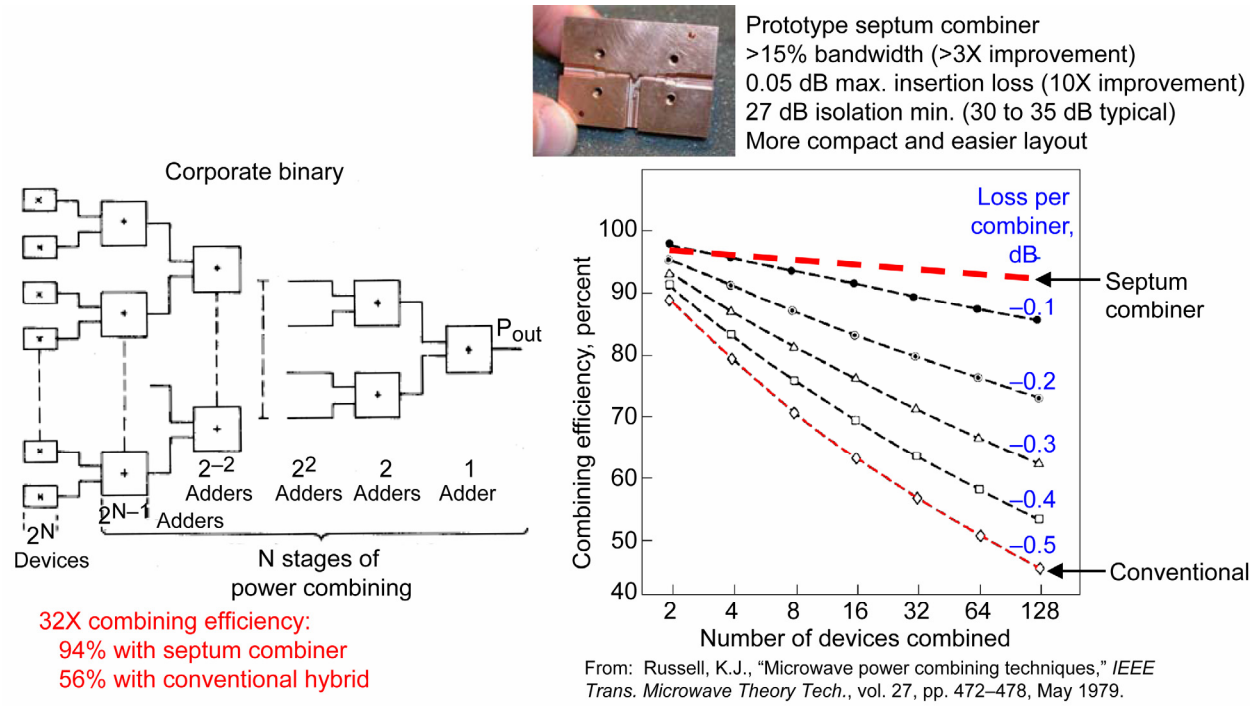


Figure 6–11.—Septum combiner benefits.

6.2.2.3. SSPA Summary

SSPA technology is summarized in table 6–4. Advances in MMIC technology and power combining are leading to the development of SSPAs capable of competing at the lower TWTA power levels (120 to 150 W) (ref. 6–12). Typically, microwave amplifiers based on vacuum-tube technology are widely used in space telecommunication applications due to their high power capability, good efficiency, and established flight history. However, SSPA technology offers

TABLE 6–4.—A SUMMARY OF SSPA TECHNOLOGY WITH ESTIMATES OF TECHNOLOGY READINESS LEVEL, POWER LEVELS, AND SYSTEM EFFICIENCY

Issue	Status or comment
Current TRL of key SSPA-combining technologies	TRL 5 and 6
Best power-combining option for high-power SSPAs	Phased arrays offer the lowest loss combining (highest system efficiency) while offering the advantages of the ability to scan and provide multiple beams
Advantages of waveguide combining	TWTA alternative when phase control is not needed
Power levels obtainable by SSPAs	Estimated power levels: 150 W, 20% PAE GaAs based in 3 to 5 years 450 W, 30 to 40% PAE GaN based systems in 5 to 7 years 20 W available today at 8% PAE
Key risk issues	Development of GaN MMICs with high efficiency (48% PAE) to make 40% system efficiency obtainable (ref. 6–12)
Mass of 150 W systems	3.7 to 4.6 kg (ref. 6–12)
Development of kW-level systems	Ground transmitters in 3 to 5 years, space application in 5 to 7 years with availability of GaN and higher efficiencies
Technology readiness of kW systems	Similar to combining of TWTAs, but dependent on GaN development for efficiency
Unknown system reliability	Reliability analysis needed to assess overall system reliability. Investigate and include in analysis all known failure modes for amplifier, combining network, power and signal distribution network/manifold

potential for highly distributed feeds with active control that can be utilized for adaptive beam pointing and surface distortion compensation. Further, the wide commercial technology base that exists for solid-state amplifiers will likely lead to significant cost reductions and ongoing reliability improvements that will make this technology increasingly compelling. In addition, continued technical advances such as those in wide-bandgap gallium nitride (GaN) semiconductors offer the potential for increased MMIC power and efficiency. Such technology advances raise the expectation that a new class of high-power, high-efficiency SSPAs will be developed as alternatives to vacuum tube technology. A detailed analysis of the reliability associated with SSPA-based amplifiers is needed.

6.2.3 Summary of RF Amplifier and Power-Combining Technology and Solid-State Power Amplifier (SSPA) Technology

In this report Ka-band RF power levels ranging between 10 and 10,000 W are considered for generating the required EIRP necessary for high rate data delivery from mars. While SSPA technologies are usually associated with lower power levels, in-waveguide and spatial power-combining techniques provide scalability to SSPA technology that may extend the effective operating range of space qualified of solid-state-based systems to nearly the 100 W level in the short term and to the 1 kW level with a sustained research effort. Vacuum tube electronics

currently achieve power levels between 10 W and 3 kW with a single device. As with solid-state technology power-combining techniques extend the range of achievable power levels by as much as two orders of magnitude. However, note that power levels significantly above 1 kW lead to multipaction and breakdown issues even in passive devices and may therefore require the use of spatial power-combining techniques. Such power levels require large amounts of prime power and may only be indicated for spacecraft that have large power generating capabilities such as nuclear powered. The use of power levels above 3 kW, within a single waveguide, is not considered practical at this point.

Apart from power level, other performance-related items separate the different RF amplifier technologies such as PAE, linearity (distortion) and bandwidth. Other considerations include the supply voltage (lower is better), mass, occupied volume and the ability of the device to shed heat. TWT technology currently has superior PAE to solid-state devices and klystrons. However, improvements in solid-state device efficiency continue to occur and will likely be sustained by commercial or military efforts. Additionally, the same multistate depressed collector technology that provides TWT devices with high efficiency is also applicable to klystrons. Note; however, that because the beam is less "collectable" in a klystron, a multistage depressed collector will never offer the same efficiency improvement in a klystron as they do for a TWT. Solid-state devices can provide similar or greater levels of linearity when compared to traditional, nonlinearized TWTA technology that does not employ solid-state predistortion filters. TWTA systems provide greater bandwidth and linearity than klystrons. Note; however, that it is the combination of low distortion and high efficiency that is difficult to obtain. When considered together, TWTA technology will likely not be overtaken by solid-state technology in the foreseeable future. Note; however, that linearity may only be of concern if high order modulation is needed. Similar comments comparing TWTA, SSPA, and klystron apply to bandwidth. In vacuum tube systems the bandwidth is proportional to the supply voltage. Large bandwidths can be achieved if one is willing to accept large voltages within the RF power amplifier. Similar caveats to the bandwidth issue apply as well—given the fact that Ka-band is very high, a few percent of bandwidth can be more than most missions will ever need. Extremely wide band operation of the final power amplifier stage may only be applicable to cases when multiple bands need to be covered. The notable example in the current case is the 32-GHz science band together with the 37-GHz exploration band and/or the 26-GHz near-Earth band. These "rules of thumb" are fairly well accepted and have been stable for a significant period of time.

While much less well understood than the physical limitations associated with the different Ka-band amplifier technologies, the cost of these systems is of great importance. Currently, high power TWTA devices are extremely expensive when compared to a single low power SSPA. The underlying tenant of the power-combined SSPA research is that the overall cost of such a system will be significantly lower than that of a single high-power TWTA system. However, with the development of 180-W Ka-band tubes much of the non-recurring expense (NRE) has been paid in advance and thus the cost for manufacturing and space-qualifying a high-power TWTA will be significantly reduced in the future. Additionally, the cost of integrating a multitude of SSPAs into a single unit of comparable power to a 180-W TWTA may bring the overall cost of the system to be more than that of a single TWTA. The cost of a CW klystron is even less well understood.

Complex engineering tradeoffs concerning mass, power, cost, PAE, bandwidth, linearity, etc., are addressed by individual missions using the requirements and goals of the mission as guidance. As is done now, missions of the future will take the "pulse" of the industry and form

judgments regarding technologies that are applicable to their mission at the time that they are building their respective spacecraft. Development of low-TRL items such as an ESA with good PAE and per-element amplitude control may lead to the availability of devices that allow a mission to solve a unique problem. For example, it may be the case that the development of power-combined SSPA-based amplifiers may enable low-cost ESAs to be developed that could be used to solve issues with reflector distortion and fine-beam pointing for a high rate Mars relay spacecraft.

6.3 Solar Panels and Power Modules

6.3.1 Solar Panels

Photovoltaic solar arrays have been and currently are the most widely used power sources for satellites, both near-Earth and deep space. Over the years, spacecraft have acquired a multitude of new technologies requiring solar arrays to become more flexible and adaptable to these changes. While many new areas of photovoltaic solar arrays are being pursued, the three that will be discussed here are multijunction arrays, the stretched lens array (SLA), and thin-film arrays. These three have a good outlook towards being commonplace in the 2015 to 2030 timeframe.

6.3.1.1 Multijunction Arrays

Multijunction solar arrays represent the state of the art in solar array technology. Triple-junction arrays are at a TRL 9 and are the most commonly used types. Current missions using multijunction arrays include the Martian rovers Spirit and Opportunity and Mars Global Surveyor. Multijunction arrays have conversion efficiencies around 20 to 25 percent, with the best operating around 28 percent. After factoring in integration, performance, and cell packing knockdown factors, however, these cells have an effective array-level conversion efficiency of around 14 to 18 percent, with the best around 20 percent.

6.3.1.2 Stretched-Lens Array

The SLA is a multijunction array that uses a Fresnel lens to focus sunlight onto the solar cells (fig. 6–12), resulting in a greater concentration of sunlight on the cell then at the unconcentrated level. In 1994, the SCARLET (Solar Concentrator Array with Refractive Linear Element Technology) solar array aboard Deep Space 1 (DS–1), used a small (8.5-cm-wide aperture) silicone Fresnel lens to focus sunlight at 8× concentration onto radiatively cooled, triple-junction cells. SCARLET achieved a specific power of 45 W/kg, the best performance metric at that time. Currently, SLA's should be considered for power requirements greater than 10 kW power requirements below 10 kW, SLAs are less mass competitive. SLAs are currently at a TRL 8.

Other issues with SLAs are the operational issues, which may drive up the battery power. A larger battery may be needed for pre-array-deployment spacecraft power if the outer most panel is not planar, or for spacecraft safe-mode power during recovery from a loss of attitude event and recovery. The biggest operation impact of SLA is the need to accurately Sun-track the solar array on two axes using tracking gimbals and/or spacecraft flight mode. This is not difficult for heliocentric missions in the ecliptic (like DS–1), but becomes challenging for Earth-orbiting missions with moderate or large orbit inclinations, for example, 28.5° (typical inclination for launches from Kennedy Space Center).

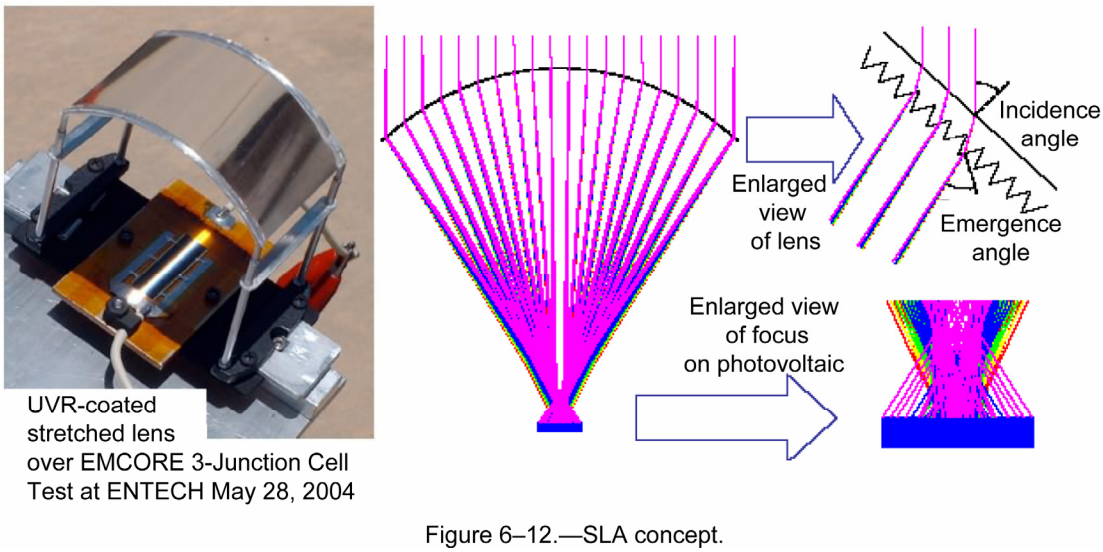


Figure 6–12.—SLA concept.

6.3.1.3 Thin-Film Arrays

Thin-film technology is one option under development for future solar arrays. Although conversion efficiencies are low, this array type, with having lightweight deployment structures, may offer specific power levels comparable to that of multijunction arrays. There are several challenging issues with thin-film arrays; they currently operate at very low efficiency levels, approximately 9 percent. At very small cell sizes, it has been shown that thin films can reach efficiencies up to approximately 17 percent, however, there are processing problems for larger areas where defects start to creep in.

Also, the radiation tolerance of thin-film arrays depends greatly on photovoltaic technology, array configuration, mission requirements, and thermal and injection annealing. The latter mechanisms recover radiation damage to thin-film solar cells, but are dependent on cell type, operating temperature, and lighting history. If the solar arrays are designed to operate hot enough (with a loss in voltage and power output), radiation damage may be recovered in real time. This real-time radiation damage recovery has not yet been demonstrated on the ground or in orbital testing.

The radiation tolerance of thin-film arrays depends greatly on photovoltaic technology, array configuration, and mission requirements. In high radiation environments, thin-films require thick shielding, which affect the mass competitiveness of thin films. Currently, thin-film arrays are at a TRL 4 or 5. There have been no tests of this technology beyond low Earth orbit (LEO). United Solar has produced a 1- by 1-ft-thin-film array, and the Air Force is planning a larger demonstration with power levels greater than 1 kW.

6.3.2 Power Modules

As power requirements for spacecraft increase with future missions, both terrestrial and deep space, advanced technology in energy storage will be required, as shown in figure 6–13. Many areas of energy storage have been studied, and three that hold promise for the near future are discussed in this report. These technologies are advanced batteries, fuel cells, and flywheel storage. It should be noted that while nuclear power systems have been shown to provide the best mass efficiency for very large power outputs (>100 kW), their discussion in this report is limited to the content of figure 6–14, which in comparing the power system masses for solar and nuclear sources as a function of distance from the Sun, confirms the inevitable mass advantage of nuclear power at the outer planets.

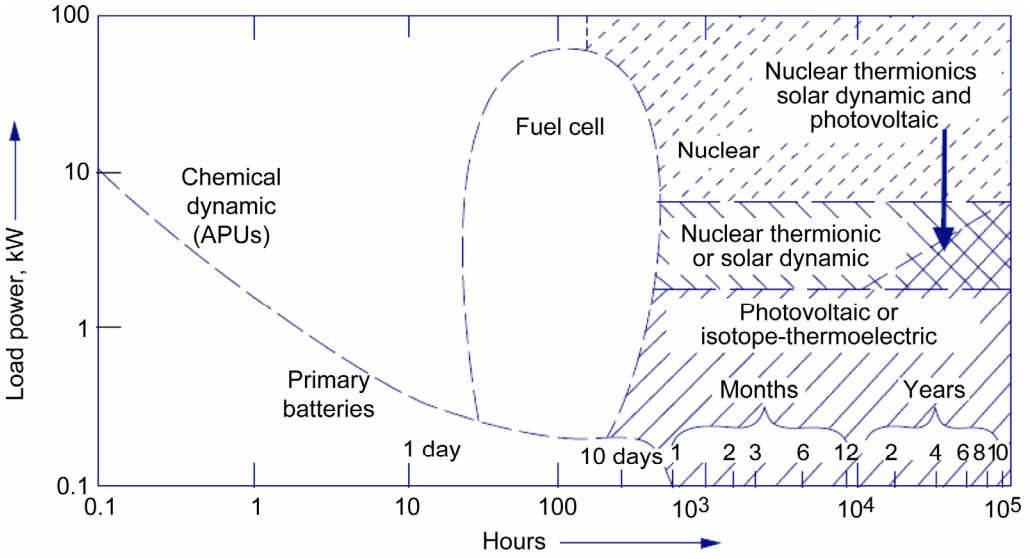


Figure 6–13.—Approximate ranges of application of different power sources (ref. 6–10).

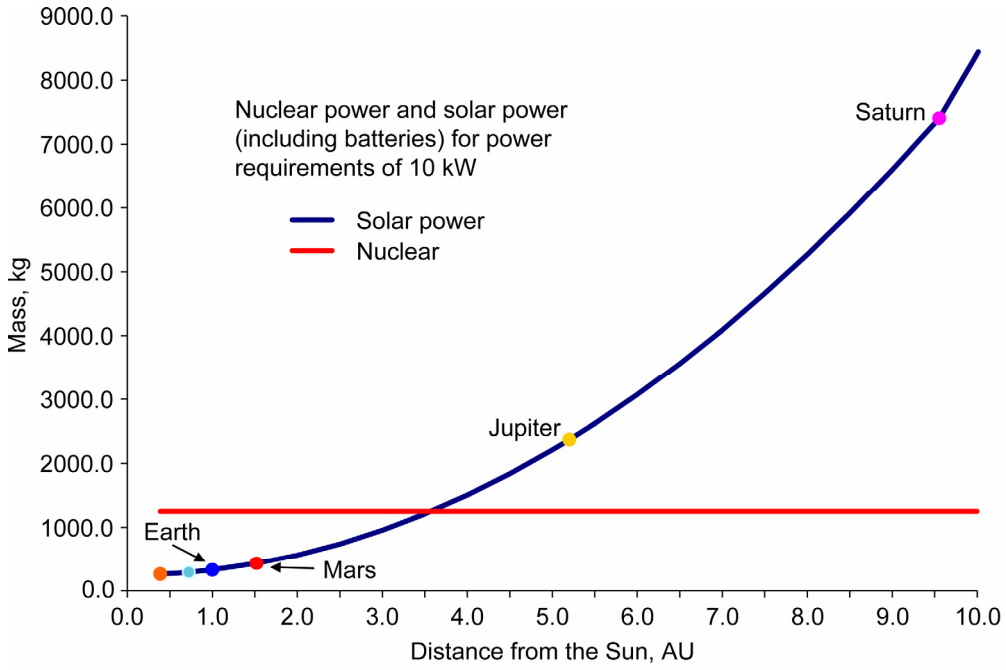


Figure 6–14.—Crossover point for nuclear and solar power mass estimates at 10 kW power as a function of distance from the Sun.

6.3.2.1 Battery Technology

Current and near-term missions will continue to use nickel-based power sources (TRL 9), such as the nickel-cadmium (Ni-Cd) and nickel-hydride (Ni-H_2) systems in current use. Ni-H_2 systems provide operation at deeper depths of discharge while providing a life comparable to Ni-Cd, a lighter weight energy storage system.

Second-generation systems will be lithium-based batteries (TRL 7). Compared to the above, these operate over much wider temperature ranges and consume less mass and volume. Researchers expect lithium-based batteries to be implemented in space-science missions within 5 years.

For far-term missions (~10 years), a possible third-generation system using lithium-based polymer electrolyte batteries is anticipated. These batteries, currently at the TRL 5 stage, will have the potential to provide five times the energy of current energy storage systems, while cutting mass and volume by one-third and one-tenth, respectively.

Some challenges to be addressed for lithium-based power systems are improvements in energy density and specific energy, and the capability of long calendar and cycle life (refs. 6–14 to 6–21).

6.3.2.2 Regenerative Fuel Cells

Regenerative, or secondary, fuel cells use hydrogen and oxygen to produce electrical power and water. An external power source then electrolyzes the water to replenish hydrogen and oxygen.

Figure 6–15 shows storage energy density versus power density of batteries and fuel cells. This data shows that fuel cells could satisfy a mission requiring neither high power nor high energy, but rather a power system that is energy and/or power dense for its applications. However, the key issue evident in the figure is that for fuel cells to be competitive with batteries, the reactant storage pressure must be 600 atmospheres (~8800 psi) or greater. At this pressure, fuel cells would offer volumetric advantages over batteries in some applications. Current fuel cell systems operate at a maximum pressure of ~20 atmospheres (~400 psi) and are at a TRL 4 and 5.

6.3.2.3 Flywheel Energy Storage System

Flywheel storage is a proven technology for spacecraft attitude control systems, and thus becomes an alternative technology that should be considered for future space applications. Flywheel technology can provide a very high usable specific energy (up to 300 W/kg), higher efficiency than current power systems (such as batteries and solar cells), and long cycle life (90 000 cycles at 90 percent depth of discharge). Integration with the attitude control system could provide less total hardware economy.

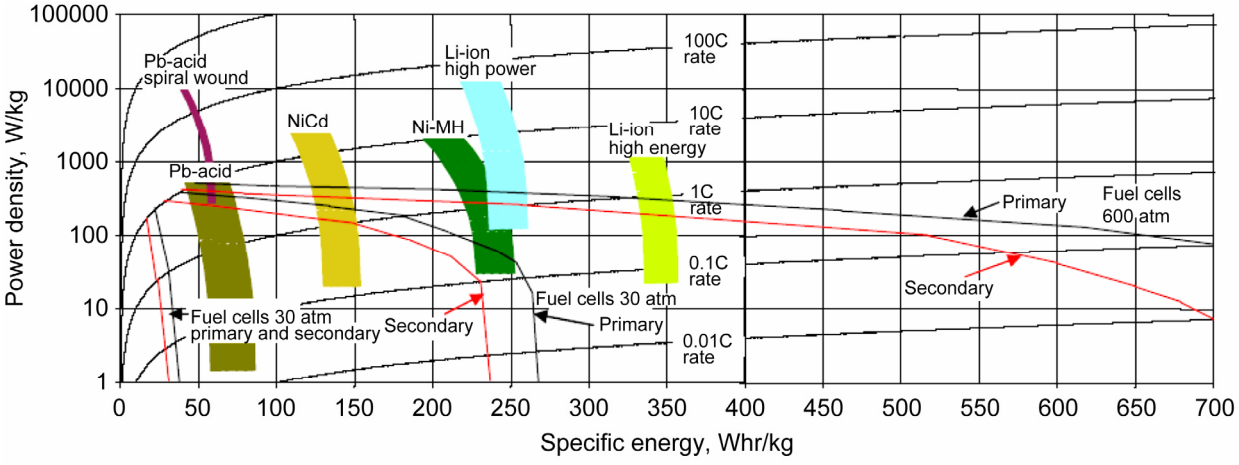


Figure 6–15.—Energy storage volumetric density (Whr/kg) as a function of power density (W/kg) (ref. 6–19).

This technology, while proven, is still in the early stages for large power outputs, high efficiencies, and long-life capability. In order for flywheel energy storage technology to be viable, advances in high-strength composite materials, highly efficient high-speed motor operation and control, and magnetic bearing levitation need to be addressed (refs. 6–24). Based on current estimates, the capabilities mentioned would be available for far-term (>10 years out) missions. Advanced flywheel technology currently operates at a TRL 2 to 3.

6.3.2.4 Power System Technology Assessment

Below (table 6–5) is a mass projection based on parameters based on a range of power requirements for future space missions. These estimates do not include the electronics systems and are calculated for the technologies mentioned above.

TABLE 6–5.—POWER SYSTEM TECHNOLOGY ASSESSMENT FOR DEEP SPACE APPLICATIONS

Technology at 2010	**Solar arrays**	**Batteries**		**Total SA + batteries**		**Nuclear**	**Fuel cells**	**Flywheel**
	MJ	**Ni-H_2**	**Li-Ion**	**Ni-H_2**	**Li-Ion**			
Specific power, W/kg (at Mars distance)	55	40	50			8	100	40
TRL Level	9	9	5 to 9			9	4 to 5	2 to 3
Typical lifetime, yr	10	60000 cycles	1500 cycles			10	0.03	90000 cycles
Power, W	***Mass, kg***							
200	3.6	5.0	4.0	8.6	7.6	25.0	2.0	5.0
1000	18.2	25.0	20.0	43.2	38.2	125.0	10.0	25.0
10000	181.8	250.0	200.0	431.8	381.8	1250.0	100.0	250.0
100000	1818.2	2500.0	2000.0	4318.2	3818.2	12500.0	1000.0	2500.0

Technology at 2020	**Solar arrays**	**Batteries**		**Total SA + batteries**		**Nuclear**	**Fuel cells**	**Flywheel**
	MJ	**Li-Ion**	**Li-Ion + electrolyte**	**Li-Ion**	**Li-Ion + electrolyte**			
Specific power, W/kg (at Mars distance)	91	50	100			10	200	150
Typical lifetime, yr	10	1500 cycles	1500 cycles			10	0.03	90000 cycles
Power, W	***Mass, kg***							
200	2.2	4.0	2.0	6.2	4.2	20.0	1.0	1.3
1000	11.0	20.0	10.0	31.0	21.0	100.0	5.0	6.7
10000	109.9	200.0	100.0	309.9	209.9	1000.0	50.0	66.7
100000	1098.9	2000.0	1000.0	3098.9	2098.9	10000.0	500.0	666.7

TABLE 6–5.—CONTINUED.

Technology at 2030	Solar arrays	Batteries		Total SA + batteries		Nuclear	Fuel cells	Flywheel
	TF	Li-Ion + electrolyte	Li-Ion + poly electrolyte	Li-Ion + electrolyte	Li-Ion + poly electrolyte			
Specific power, W/kg (at Mars distance)	190	100	150			15	250	300
Typical lifetime, yr	10	1500 cycles	1500 cycles			10	0.03	90000 cycles
Power, W	*Mass, kg*							
200	1.1	2.0	1.3	3.1	2.4	13	0.8	0.7
1000	5.3	10.0	6.7	15.3	11.9	67	4.0	3.3
10000	52.6	100.0	66.7	152.6	119.3	667	40.0	33.3
100000	526.3	1000.0	666.7	1526.3	1193.0	6667	400.0	333.3

6.4 Power System Technologies—Fact Summary and Conclusions

6.4.1 Summary of RF Amplifier and Power-Combining Technology

The key design issues for a high-power amplifier are output power, efficiency, mass, and heat dissipation. Today, a single TWTA will produce one to two orders of magnitude more RF output power than a single SSPA. However, technology advances (e.g., wide-bandgap semiconductors) suggest that future SSPAs may rival today's TWTs in output power and efficiency. Other vacuum tube technologies are applicable to the Mars relay application including EIK. While klystrons are typically narrowband devices, the bandwidth limitation is not restrictive for the current application and they are able to provide extremely high power in a single device. Both amplifier technologies can benefit from some form of power combining to achieve output power higher than is available from a single device. Power combining can be implemented in a waveguide, but can also be quasi-optical (multiple amplifiers illuminate the antenna reflector).

Interplanetary spacecraft carry as much as a 35-W Ka-band TWTA, but there are laboratory demonstrations of Ka-band 180-W TWTs (ref. 6–2). The feasibility of 1-kW or even 2.5-kW Ka-band coupled-cavity TWTs has been cited. In the long term (2020), single-device technology may achieve up to 10 kW (presently very low TRL). For the foreseeable future, transmitted power above a few kilowatts will require power combining, for example, magic-T alone or magic-T/hybrid combinations.

Solid-state devices (GaN and GaAs) now achieve 1 to 10 W, with demonstrated efficiencies of 30 to 50 percent, and the ability to operate at extremely high temperatures (>250 °C). A 120-W-class Ka-band amplifier is feasible; work is being pursued to combine multiple 120-W-class amplifiers to develop a 1-kW-class solid-state transmitter for ground applications. The approaches for kilowatt-level power are the same as power combining of TWTAs.

Separation between the amplifier and the antenna horn or use of waveguide power combining necessitates a waveguide transmission line. Existing thin-walled, low-loss waveguide appears to be of marginal utility for high-power systems (above 100 W). Thermal issues are significantly reduced by placing the high-power amplifiers directly adjacent to the antenna feeds or using quasi-optical architectures. Evaluation of the reliability of SSPA architectures is needed.

6.4.2. Summary of Solar Panel and Power-Module Technology

6.4.2.1 Solar Panels

Photovoltaic solar array technology shows at least three promising areas of pursuit: multijunction arrays (TRL 9), the SLA (TRL 9), and thin-film arrays (TRL 4 and 5). Though multijunction solar arrays are the current state of the art, triple-junction arrays may reach a saturation efficiency around 30 percent, after which the technology will move towards thin-film arrays. SLAs are mass-competitive for high-power requirements (>10 kW).

Thin-film arrays can produce the same specific power levels as multijunction arrays, but at almost half the efficiency. A second challenging issue is radiation tolerance; currently thin-film arrays in high-radiation environments require mass-consuming thick shielding.

6.4.2.2 Power Modules

Current and near-term missions use Ni-Cd or Ni-H_2 battery systems. Second-generation battery systems based on lithium offer operational advantages (TRL 6 by 2020 to 2025) in temperature range and mass/volume reduction, pending resolution of challenges in energy density, specific energy, and lifetime.

Fuel cells have a long cycle life, lower weight, and good reliability/maintainability. Flywheel storage is a proven technology in attitude control that could be beneficially integrated with RF power generation. Areas requiring advances include high-strength-composite materials, efficient high-speed motors and controller, and magnetic bearing levitation.

6.5 Complexity of the Power Subsystem

Finding a simple way to characterize complexity is a key to the issue addressed in chapter 7, where we consider the joint optimization of the choice of antenna and power level to meet a given EIRP requirement. The optimization process is primarily mass based, but relies in part on assessing the technological complexity of both the antenna and power subsystem components. Such characterization is multidimensional in general, and must be simplified for practical use. (See ch. 5 for complexity characterization for antennas.) For the technologies discussed in this chapter it is almost always the case that complexity, or technical risk, associated with the technology is strongly correlated with the output power level. Based on this observation we can construct a complexity model for the power subsystem based on output power alone.

Increasing subsystem complexity is ranked by choice of an integer from 1 to 5, depending on an assumed set of technology break points that separate power levels. See chapter 7 for greater detail.

6.6 References

6–1 Weekley, J.A.; and Mangus, B.J.: IVEC 2004, IEEE 04EX786, 2004, p. 263.

6–2 Menninger, W.L., et al.: IVEC 2005, ESA WPP–246, 2005, p. 45.

6–3 Komm, D.S.: Private Communication. 2005.

6–4 Wintucky, E.; Simons, R.; Freeman, J.; Zaman, A.; Jones, R.; Carek, D; Bernhard, J.; Lesny, G.; and Glass, J.: Ka-Band Technology Developments for Space Communications at the NASA Glenn Research Center, Proc. 10th Ka-Band and Broadband Communications Conf., pp. 501–508. Vicenza, Italy, Sep. 30–Oct. 2, 2004.

6–5 Wintucky, E.; Simons, R.; Vaden, K.; Lesny, G.; and Glass, J.: High Power Combining of Ka-Band TWTs for Deep Space Communications. Proceedings of IVEC/IVESC 2006, pp. 63–64. Monterey, CA, Apr. 25–27, 2006.
6–6 Vaden, K.; and Simons, R.: Computer Aided Design of Ka-Band Waveguide Hybrid Junctions for Power Combining Architectures in Interplanetary Spacecraft. Proceedings of IVEC/IVESC 2006, pp. 383–384. Monterey, CA, Apr 25–27, 2006.
6–7 Khan, P.; Epp, L.; and Silva, A.: (Jet Propulsion Laboratory, California Institute of Technology); and Roland Shaw; and David Sanderlin (Rock Systems, LLC): Ka-Band Wide-Bandgap Solid-State Power Amplifier Architecture Development. Final Report for Task Plan 97–7813, Internal Document, Mar. 11, 2005.
6–8 Epp, L.; Khan, P.; and Silva, A.: "Ka-Band Wide-Bandgap Solid-State Power Amplifier: Hardware Validation," The Interplanetary Network Progress Report, Jet Propulsion Laboratory, Pasadena, CA, vol. 42–163, November 15, 2005, pp. 1–22.
6–9 Khan, P.; Epp, L.; and Silva, A.: Ka-Band Wideband-Gap Solid-State Power Amplifier: General Architecture Considerations. The Interplanetary Network Progress Report, Jet Propulsion Laboratory, Pasadena, CA, vol. 42–162, Aug. 15, 2005, pp. 1–19. http://ipnpr/progress_report/42-162/162F.pdf
6–10 Khan, P.; Epp, L.; and Silva, A.: Ka-Band Wideband-Gap Solid-State Power Amplifier: Architecture Identification. The Interplanetary Network Progress Report, Jet Propulsion Laboratory, Pasadena, CA, vol. 42–162, Aug. 15, 2005, pp. 1–16. http://ipnpr/progress_report/42-162/162E.pdf
6–11 Khan, A.R.; Epp, L.W.; Hoppe, D.J.; and Kelley, D.T.: Thin-Film Resistive Septum Waveguide Power Combiner. Provisional Patent Application No. 48,467, CIT File No.: CIT–4300–P, filed: Jan. 21, 2005.
6–12 Khan, P.; Epp, L.; and Silva, A.: Ka-Band Wideband-Gap Solid-State Power Amplifier: Architecture Performance Estimates. To appear in The Interplanetary Network Progress Report, Jet Propulsion Laboratory.
6–13 Miller, D.; and Kessee, J.: Spacecraft Power Systems. http://ocw.mit.edu/NR/rdonlyres/Aeronautics-and-Astronautics/16-851Fall2003/9E3D57EC-1476-4ED6-A38F-1A221AFB1534/0/l3_scpowersys_dm_done2.pdf
6–14 Jones, P.; and Spence, B.: Spacecraft Solar Array Trends. AEC-Able Engineering Company, Inc., 1999.
6–15 Brandhorst, H.; O'Niell, M.; and Eskenazi, M.: Stretched Lens Array (SLA) Technology Update. 21st AIAA International Communications Satellite Systems Conference, Monterrey, May 2004.
6–16 Hoffman, D.; Kerslake, T.; Hepp, A.; Jacobs, M.; and Ponnusamy, D.: Thin-Film Photovoltaic Solar Array Parametric Assessment. NASA/TM—2000-210342, AIAA–2000–2919, July 2000.
6–17 Murphy, D.; Eskenazi, M.; White, S.; and Spence, B.: Thin-Film and Crystalline Solar Cell Array System Performance Comparisons. 2003 IEEE Conference, 2003.
6–18 White, S.; Douglas, M. Spence; B. Jones; P. and Piszczor, M.: Development of an UltraFlex-Based Thin Film Solar Array For Space Applications. AEC-Able Engineering, NASA Glenn, 2003.

6–19 Piszczor, M.; O'Niell, M.; Eskenazi, M.; and Brandhorst, H.: Stretched-Lens Photovoltaic Concentrator Arrays for NASA's Moon/Mars Exploration Missions. 2nd International Energy Conversion Engineering Conference, Providence, RI, Aug. 16–19, 2004.
6–20 Hegedus, S.; and Luque, A.; Status, Trends, Challenges and the Bright Future of Solar Electricity from Photovoltaics. Handbook of Photovoltaic Science and Engineering, ch. 1, pp. 1–41, 2003.
6–21 Péres-Davis, M.; Loyselle, P.; Hoberecht, M.; Manzo, M.; Kohout, L.; and Burke, K.: Energy Storage for Aerospace Applications. NASA/TM—2001-211068, IECE2001–AT–08, July 2001.
6–22 Burke, K.: Fuel Cells for Space Science Applications. NASA/TM—2003-212730, AIAA–2003–5938, Nov. 2003.
6–23 Hoffman, D.: Space Power Architectures for NASA Missions: The Applicability and Benefits of Advanced Power and Electric Propulsion. NASA/TM—2001-211081, July 2001.
6–24 Kenny, B.; Kascak, P.; Jansen, R.; and Dever, T.: A Flywheel Energy Storage System Demonstration for Space Applications. NASA/TM—2003-212346, June 2003.
6–25 Mason, L.; and Oleson, S.: Spacecraft Impacts With Advanced Power and Electric Propulsion. NASA/TM—2000-209912, Mar. 2000.
6–26 Thaller, L.; and Zimmerman, A.: Overview of the Design, Development, and Application of Nickel-Hydrogen Batteries. NASA/TP—2003-211905, June 2003.